Assimilation of Multiresolution Radiation Products into a Downwelling Surface Radiation Model

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"Water. It's about water."

Response by former Professor and Pulitzer-winning author ***Wallace E. Stegner*** *when asked what a newcomer should know about California*

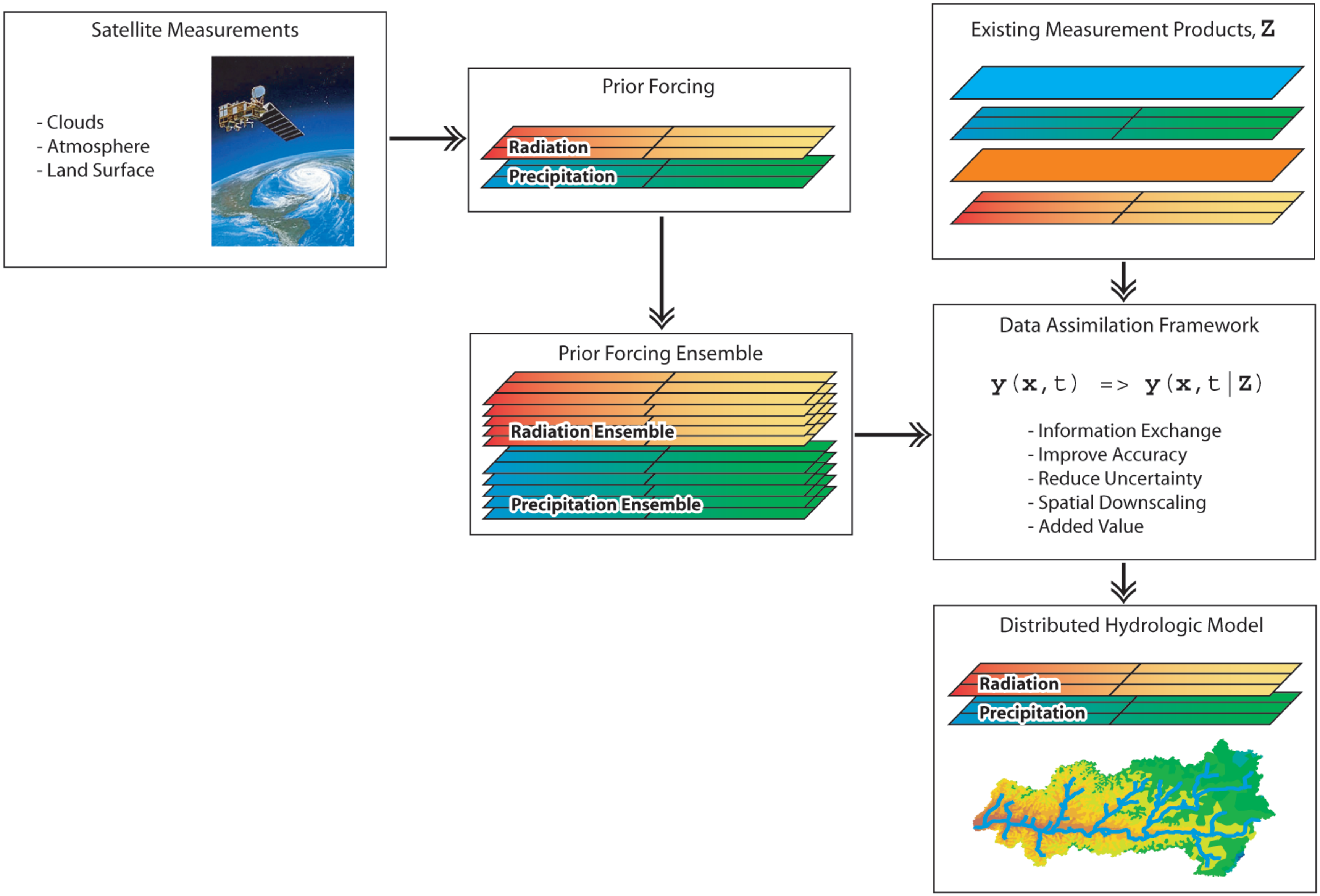
Hydrologic Cycle

I. Project Motivation
II. Satellite-based Downwelling Radiation Model
III. Ensemble-based Data Assimilation Scheme
IV. Summary of Recent Research
V. Future Work

Project Motivation

- Improve **distributed estimates** of hydrologic states / fluxes (and uncertainty)
  - **Physically-consistent**, cloud-coupled forcing
  - Utilize **satellite-borne** instruments
  - Lead to improved characterization of the **key modes of variability** in land surface states
  - Applicable in physically-based, distributed **hydrologic model** and/or **land surface model** applications

Project Approach



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Brief Overview

- **Question**: Can a relatively simple model capture space-time patterns in radiative flux?
- Satellite-derived, cloud-coupled estimates of **total downwelling radiation**
  - Merger of **VISST**, **AIRS**, and **MODIS** products
  - **High-resolution** (~4 km, ~hourly)
  - **Compares well** to ground-based radiometer network observations
- Computationally **efficient**; intended use in **ensemble data assimilation** scheme

Satellite-based Inputs

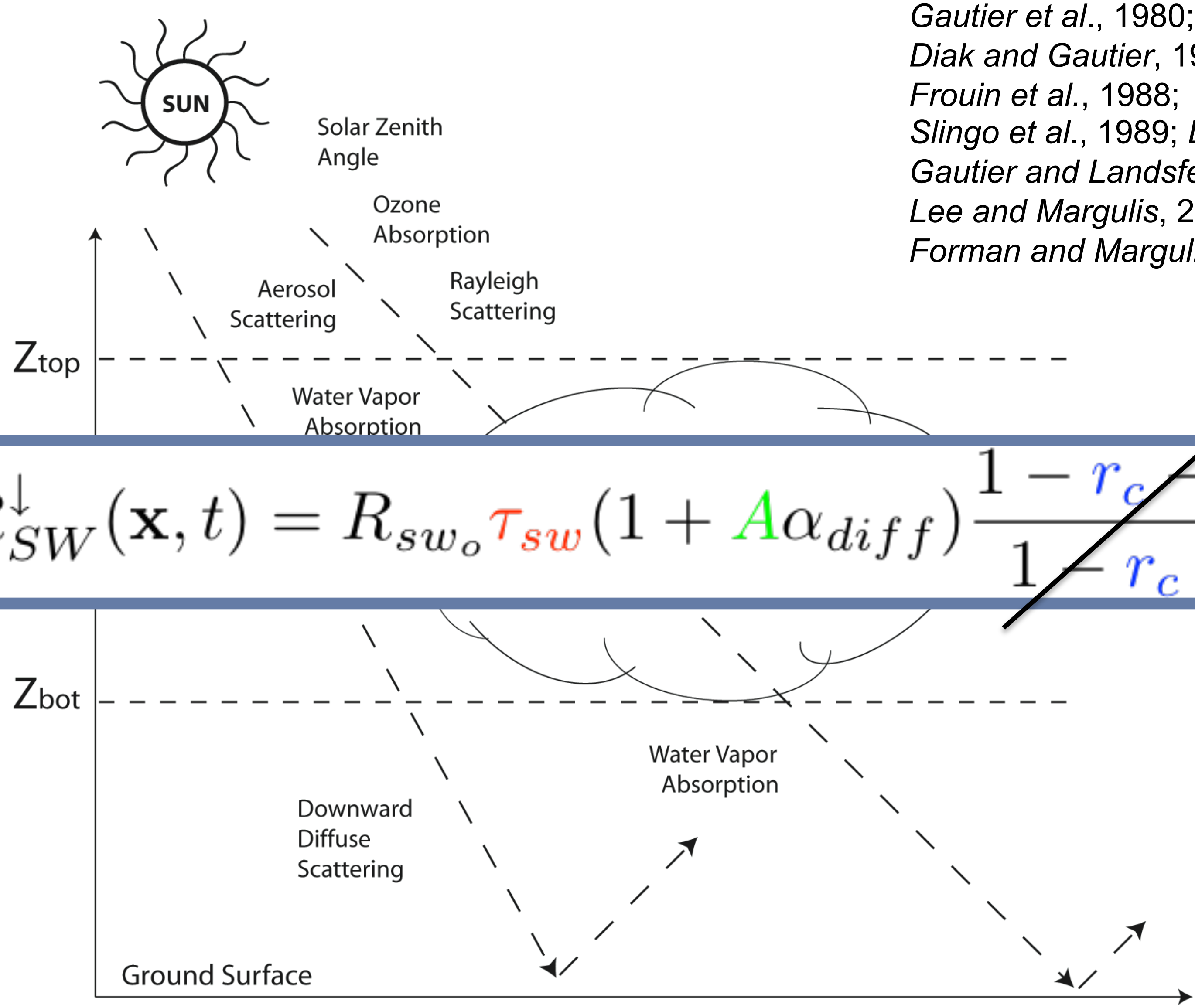
Product Name	Required State/Parameter	Orbit Type	Spectral Range	Approximate Scale Space [km]	Approximate Scale Time [days]	Model
AIRS	Near-surface air temperature and humidity	P	IR, MW, NIR, VIS	∼50	∼1/2	LW
MODIS	Black-sky albedo White-sky albedo	P	VIS	∼1	16	SW
MODIS	Total precipitable water	P	IR	∼5	∼1/2	SW
MODIS	Near-surface air temperature and humidity	P	IR, NIR	∼5	∼1/4	LW
VISST	Effective cloud height Effective cloud temperature Effective cloud pressure Cloud base height Cloud base pressure Liquid/ice cloud phase Liquid/ice water path Effective hydrometeor size	G	IR, VIS	∼4	∼1/48	LW, SW

G=Geostationary; IR=Infrared; LW=Longwave; MW=Microwave; NIR=Near Infrared; P=Polar; SW=Shortwave; VIS=Visible

Forman and Margulis [2009]

Shortwave Conceptual Model

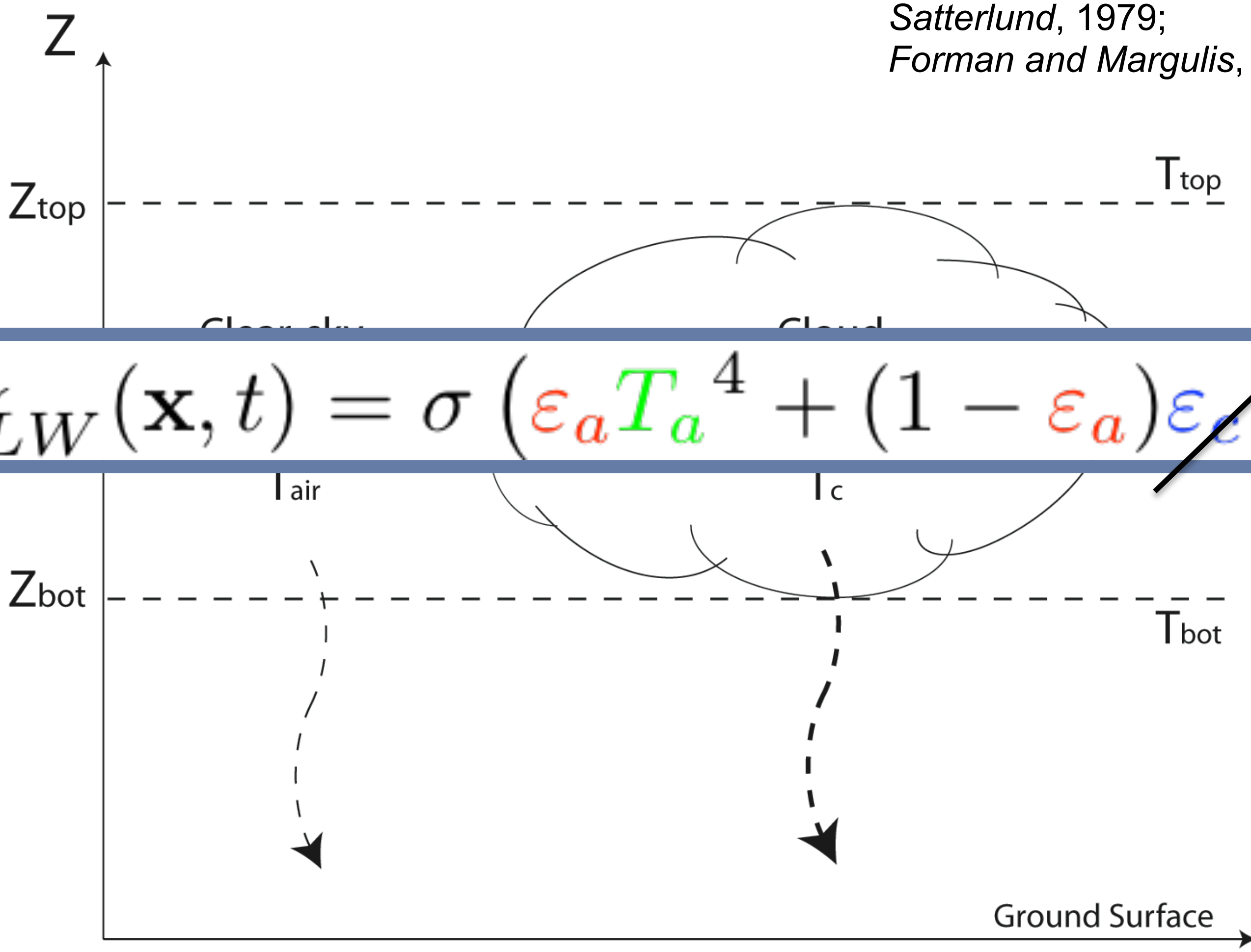
Gautier et al., 1980;
Diak and Gautier, 1983;
Frouin et al., 1988;
Slingo et al., 1989; *Liou*, 1992;
Gautier and Landsfeld, 1997;
Lee and Margulis, 2007a
Forman and Margulis, 2009



$$R^{\downarrow}_{SW}(\mathbf{x},t) = R_{sw_o}\tau_{sw}(1 + A\alpha_{diff})\frac{1 - r_c - a_c}{1 - r_c\, a_c}$$

Longwave Conceptual Model

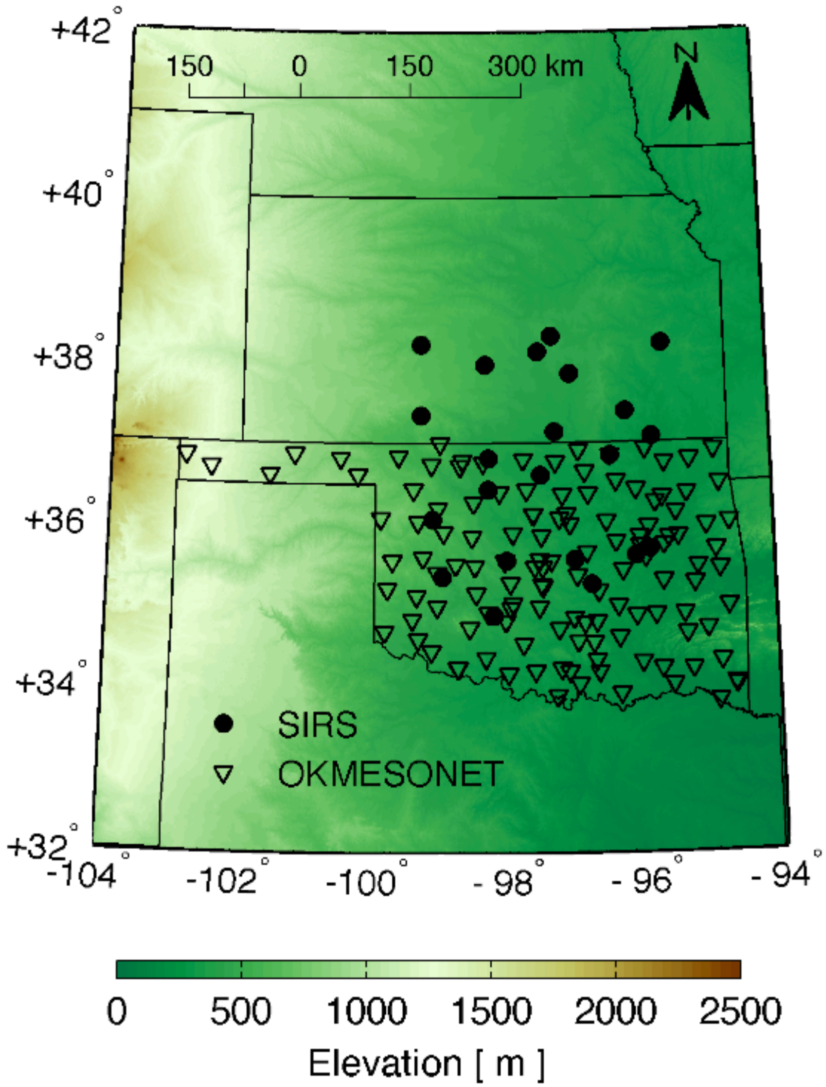
Stefan-Boltzmann Law [c. 1889];
Idso, 1980;
Satterlund, 1979;
Forman and Margulis, 2009



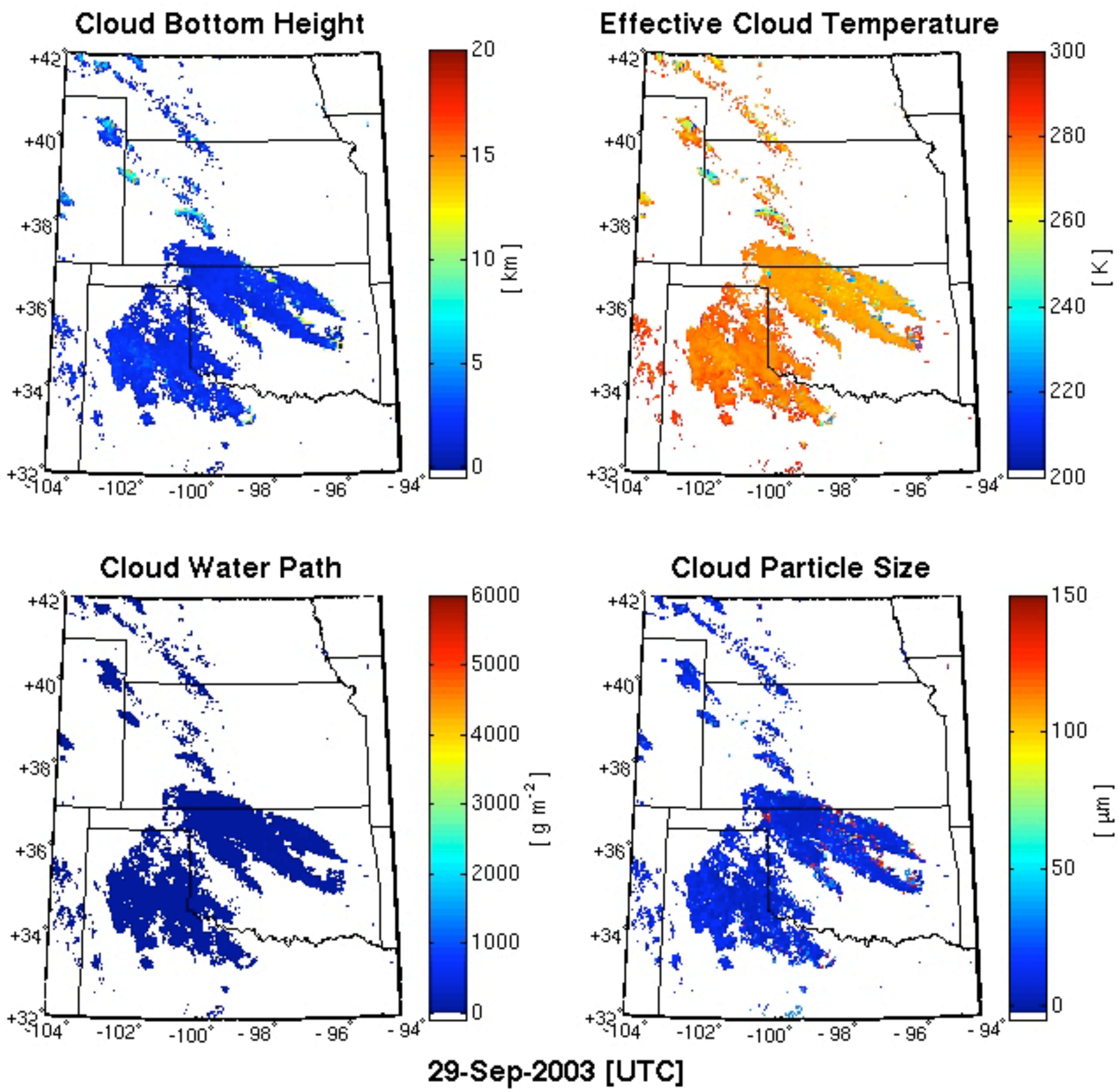
$$R^{\downarrow}_{LW}(\mathbf{x},t) = \sigma\left(\varepsilon_a T_a{}^4 + (1-\varepsilon_a)\varepsilon_c T_c{}^4\right)$$

≅0 (clear-sky)

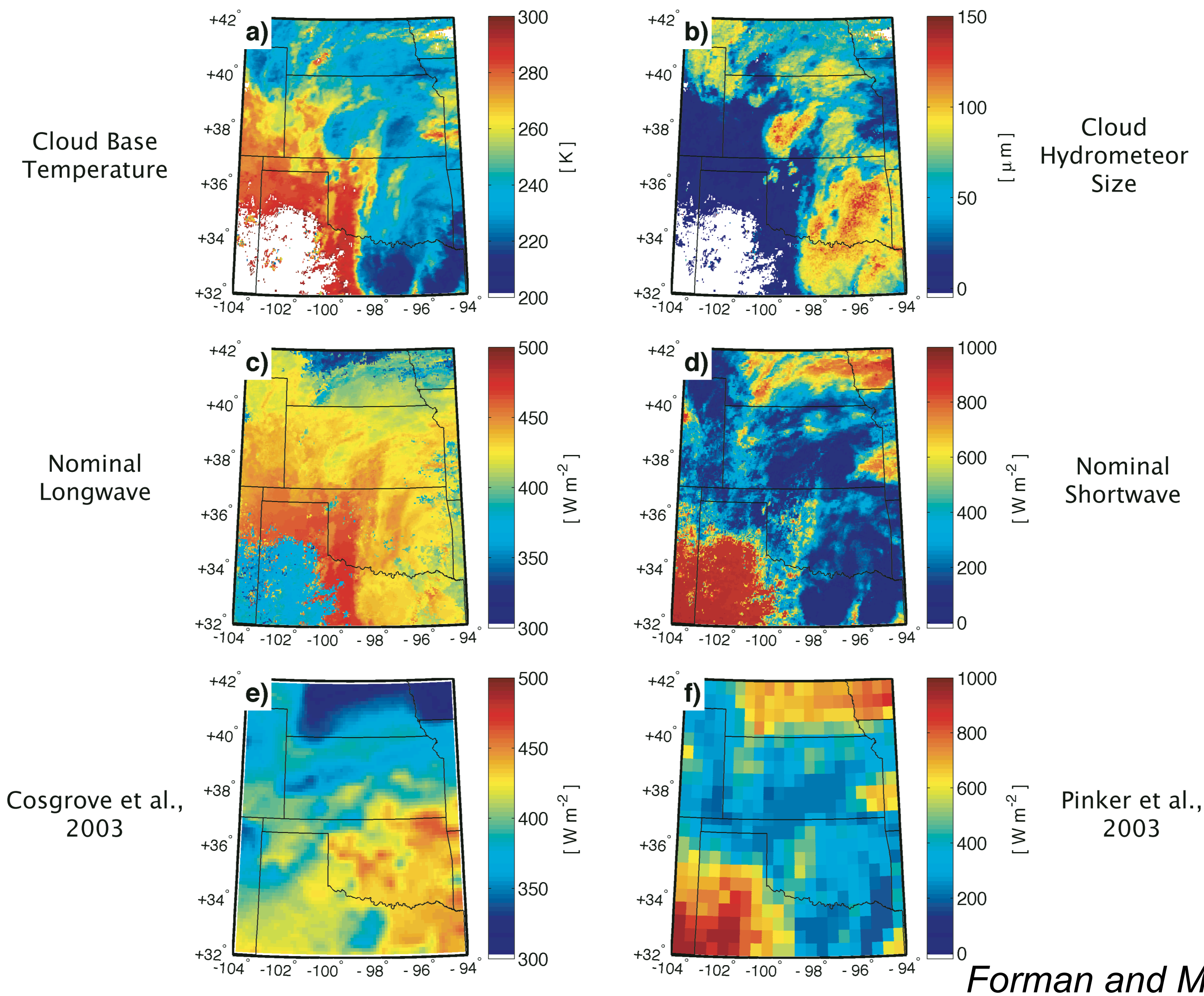
Model Application and "Verification"



Cloud States via VISST

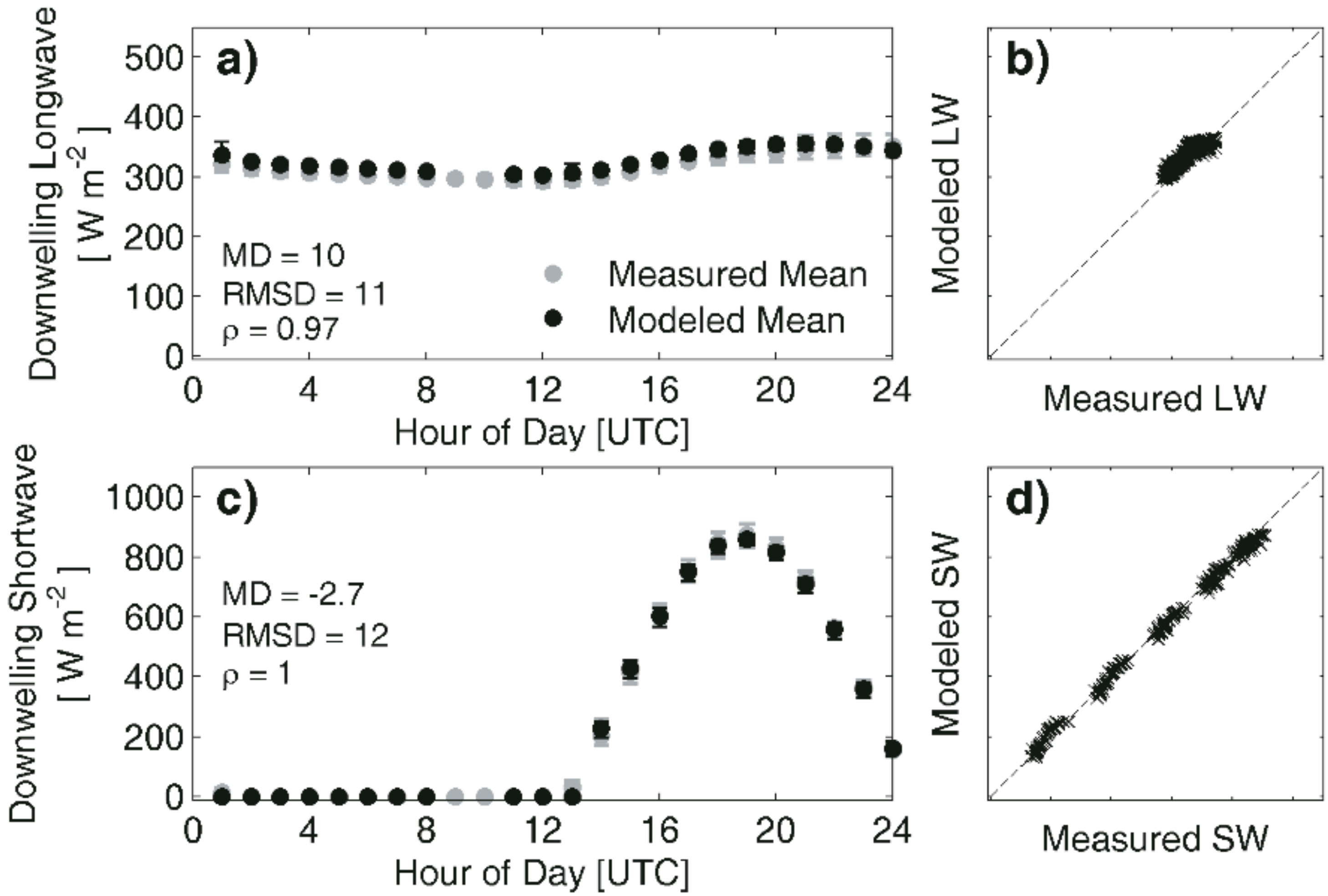


Nominal Radiation Results



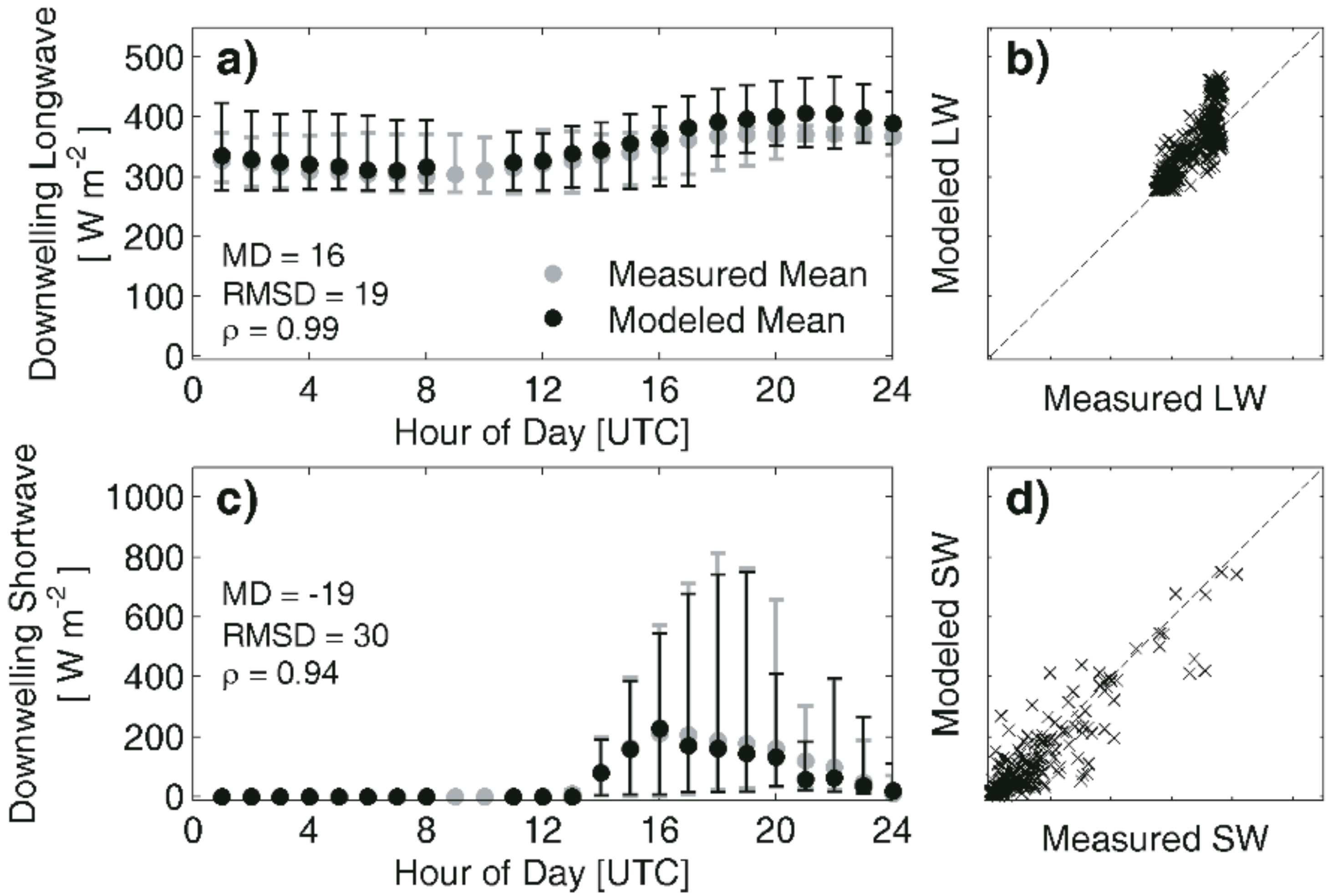
Forman and Margulis [2009]

Clear-sky Example (22 stations)



Forman and Margulis [2009]

Cloudy-sky Example (21 stations)



Forman and Margulis [2009]

Summary of Findings

- Development of **satellite-derived, cloud-coupled** downwelling radiative fluxes
  - Requires **no ground-based inputs**
- **High-resolution** (space and time)
- Computational **efficiency** lends itself to ensemble-based framework
- **Comparable** (or reduced) **error** to advanced, readily-available products

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Brief Overview

- **Question**: Can an **ensemble data assimilation** scheme capture (and **reduce**) radiative flux **uncertainty**?
  - **Perturb** atmospheric, land surface, and cloud states (**satellite inputs**)
  - **Spatially-correlated, cross-correlated**
  - **Prior** (unconditioned) ensemble
- Condition prior estimate using a Bayesian conditioning scheme
  - **Merge** model with measurements
- **Reduce uncertainty** while **adding value**

Uncertainty Characterization

Nominal Simulation

$$\mathbf{y}(\mathbf{x},t) = \begin{bmatrix} R^{\downarrow}_{LW}(\mathbf{x},t) \\ R^{\downarrow}_{SW}(\mathbf{x},t) \end{bmatrix} = \mathcal{A}\left[\mathbf{u}(\mathbf{x},t),t\right]$$

Prior Replicate

$$\mathbf{y}_j(\mathbf{x},t) = \begin{bmatrix} R^{\downarrow}_{LW,j}(\mathbf{x},t) \\ R^{\downarrow}_{SW,j}(\mathbf{x},t) \end{bmatrix} = \mathcal{A}\left[\mathbf{u}_j(\mathbf{x},t),t\right] \text{ for } j \in [1\ N]$$

Input Uncertainty

$$\mathbf{u} \sim p_{\mathbf{u}}(\mathbf{u}); \quad \mathbf{u}_j \leftarrow p_{\mathbf{u}}(\mathbf{u})$$

Multiplicative Perturbations

$$\gamma(\mathbf{x},\mathbf{L}) \sim LN\left(\mathbf{1}, \boxed{\mathbf{C}_{\gamma}(\mathbf{x})}\right)$$

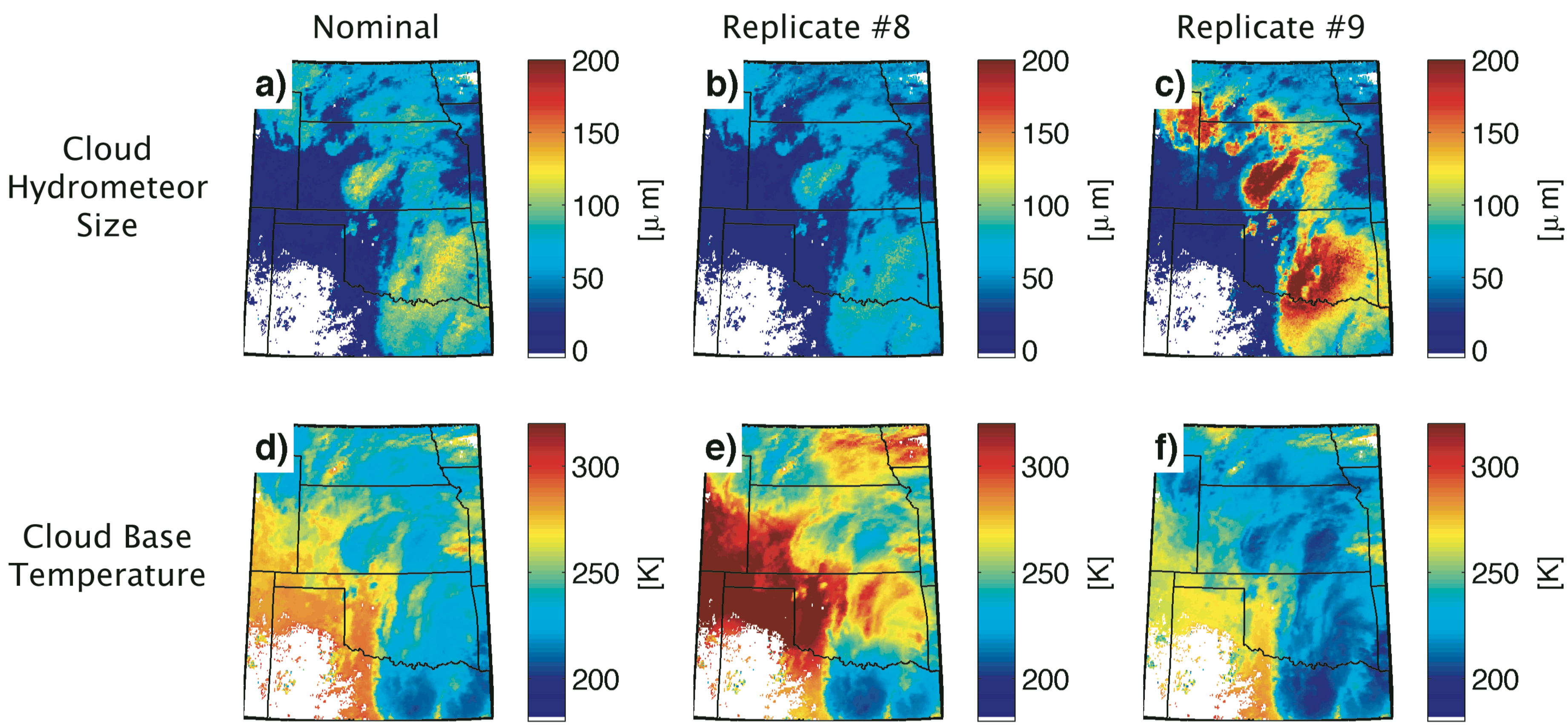
$$\mathbf{u}_j(\mathbf{x},t) = \mathbf{u}(\mathbf{x},t) \cdot \gamma_j(\mathbf{x},\mathbf{L})$$

Data-derived Covariance

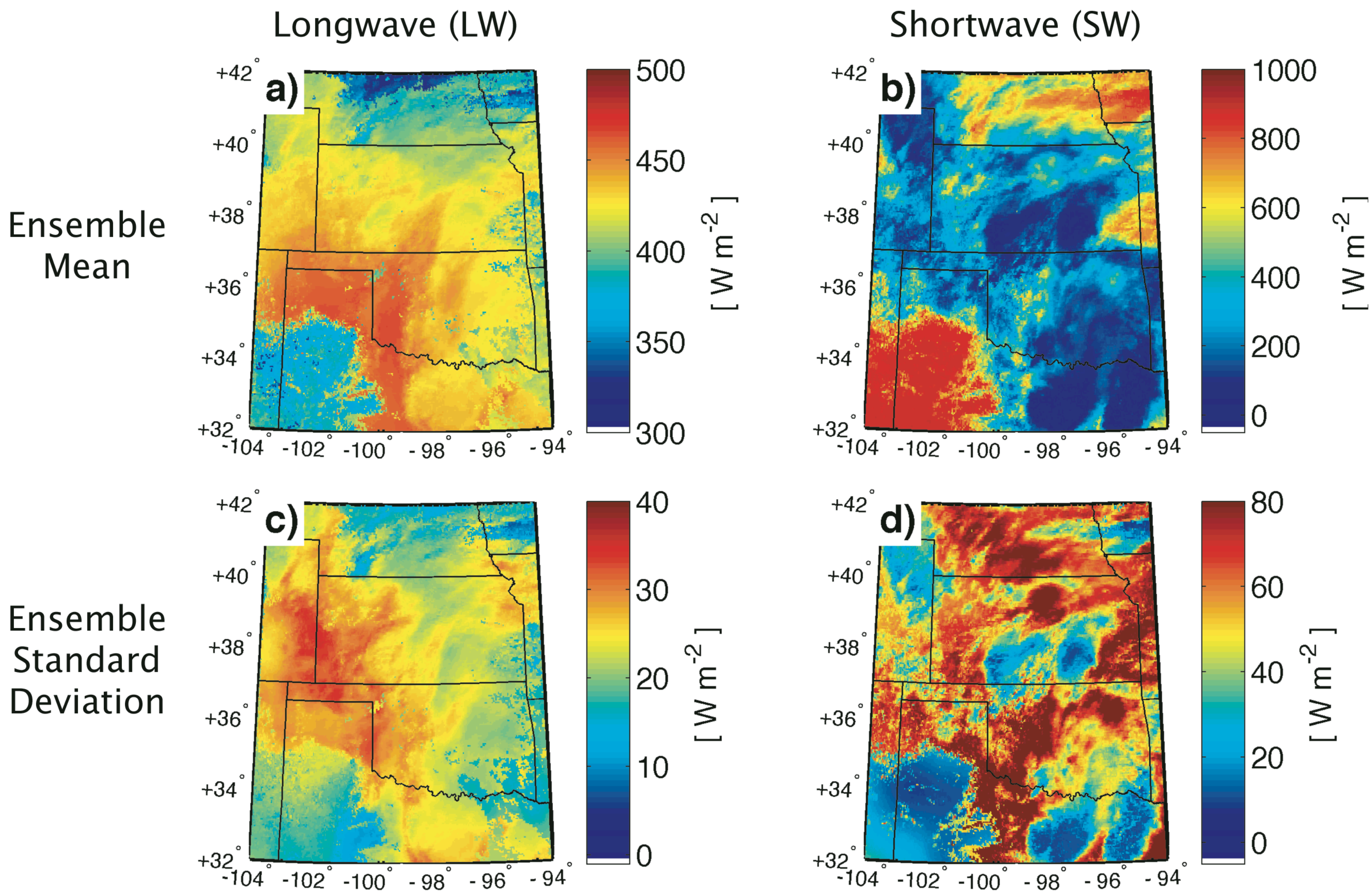
	A	AS	q_a	RS	T_a	WV	HS	T_c	WP
A	1	0	0	0	0	0	0	0	0
AS	0	1	-0.24	0.8	-0.44	-0.45	0	0	0
q_a	0	-0.24	1	-0.24	-0.18	0.18	0	0.16	-0.11
RS	0	0.8	-0.24	1	0	-0.4	0	0	0
T_a	0	-0.44	-0.18	0	1	0.24	0	0	0
WV	0	-0.45	0.18	-0.4	0.24	1	0	0	0
HS	0	0	0	0	0	0	1	-0.67	0.35
T_c	0	0	0.16	0	0	0	-0.67	1	-0.3
WP	0	0	-0.11	0	0	0	0.35	-0.3	1

[a] A, Albedo; AS, Aerosol scattering coefficient; q_a, Air specific humidity; RS, Rayleigh scattering coefficient; T_a, Air temperature; WV, Column-integrated water vapor; HS, Cloud hydrometeor size; T_c, Cloud-base temperature; WP, Cloud water path

Cross-correlated, Spatially-correlated



Prior (Unconditioned) Results



Forman and Margulis [Part 1, In Press]

Realistic Uncertainty Structure

Forman and Margulis, Part 1, In Press

e.g. *Carpenter and Georgakakos*, 2004
Lee and Margulis, 2007
Durand et al., 2008

Spatially-correlated, cross-correlated

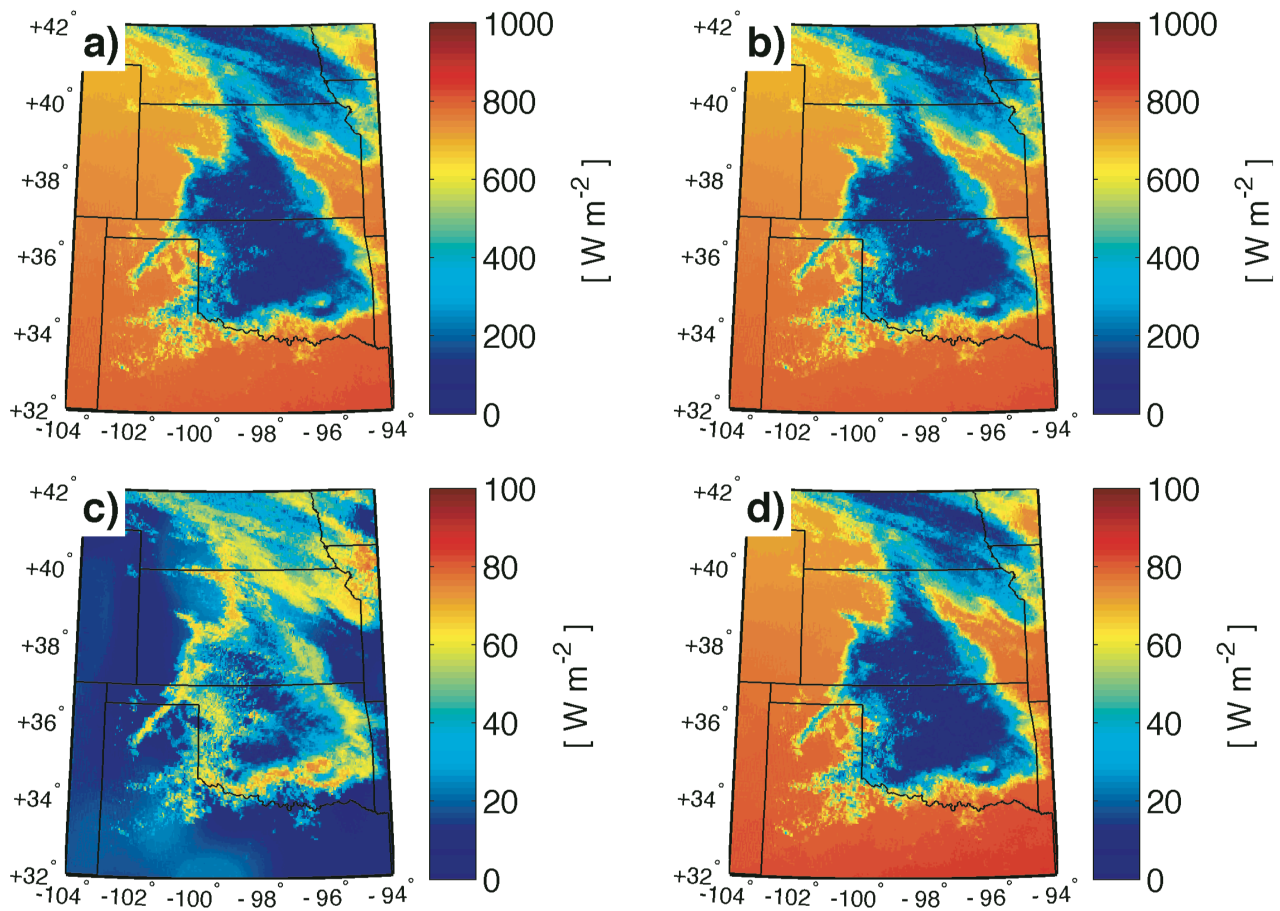
$$\gamma(\mathbf{x},\mathbf{L}) \sim \mathrm{LN}(\mathbf{1},\mathbf{C}_{\gamma}(\mathbf{x}))$$

Lumped, mutally independent :

$$\gamma \sim \mathrm{LN}(\mathbf{1},\sigma^2)$$

Ensemble Mean

Ensemble Standard Deviation



Data Assimilation Scheme

Prior Replicate:

$$\mathbf{y}_j^-(\mathbf{x},t) = \mathcal{A}\left[\mathbf{u}_j(\mathbf{x},t),t\right] \text{ for } j \in [1\ N]$$

Bayesian Merging Scheme:

$$\mathbf{y}_j^+(\mathbf{x},t|Z) = \mathbf{y}_j^-(\mathbf{x},t) + \mathbf{K}\left[Z + v_j - \mathcal{M}\left(\mathbf{y}_j^-(\mathbf{x},t),t\right)\right]$$

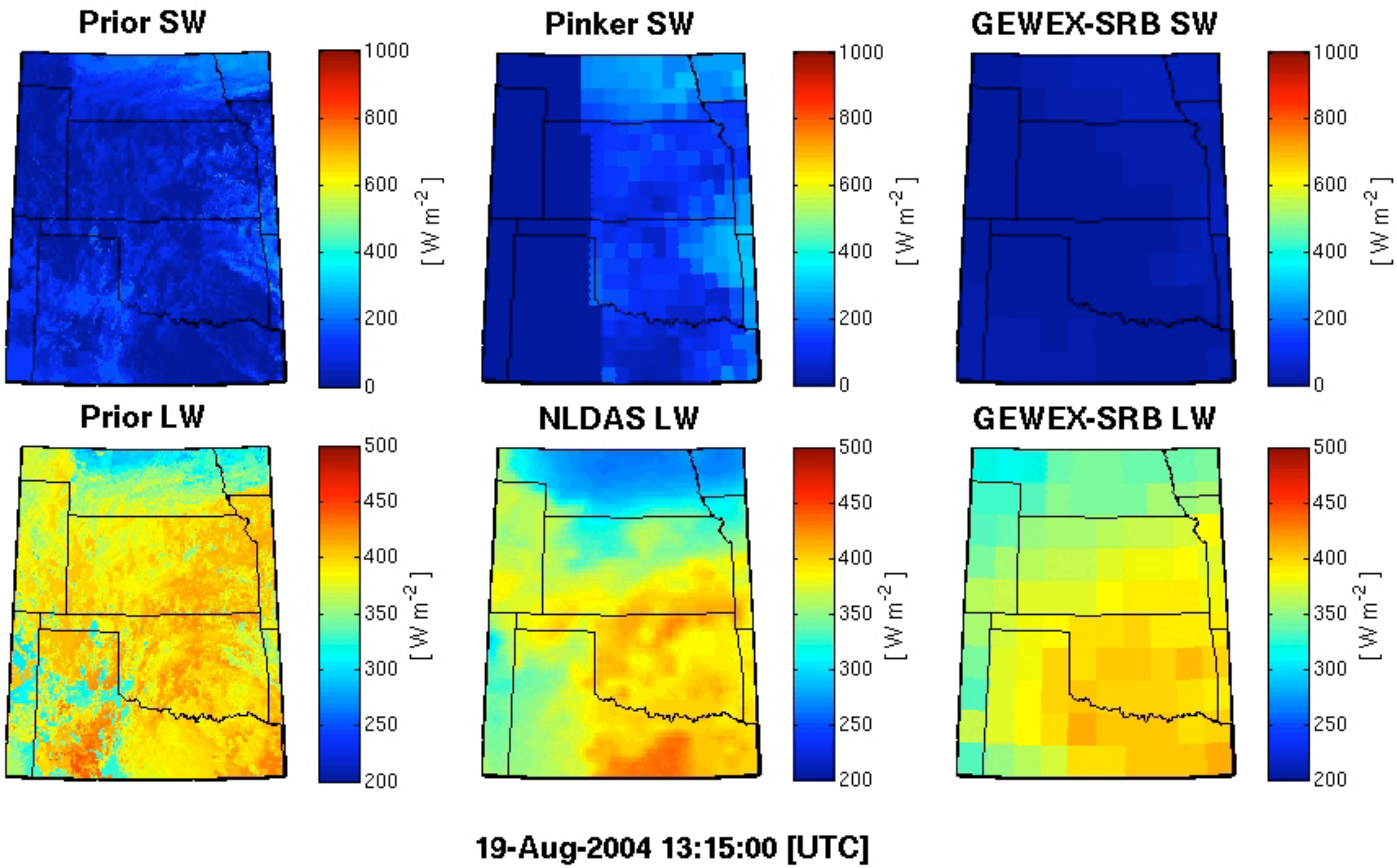
Where

Gain Matrix: $\mathbf{K} = \mathbf{C}_{yz}[\mathbf{C}_{zz} + \mathbf{C}_v]^{-1}$

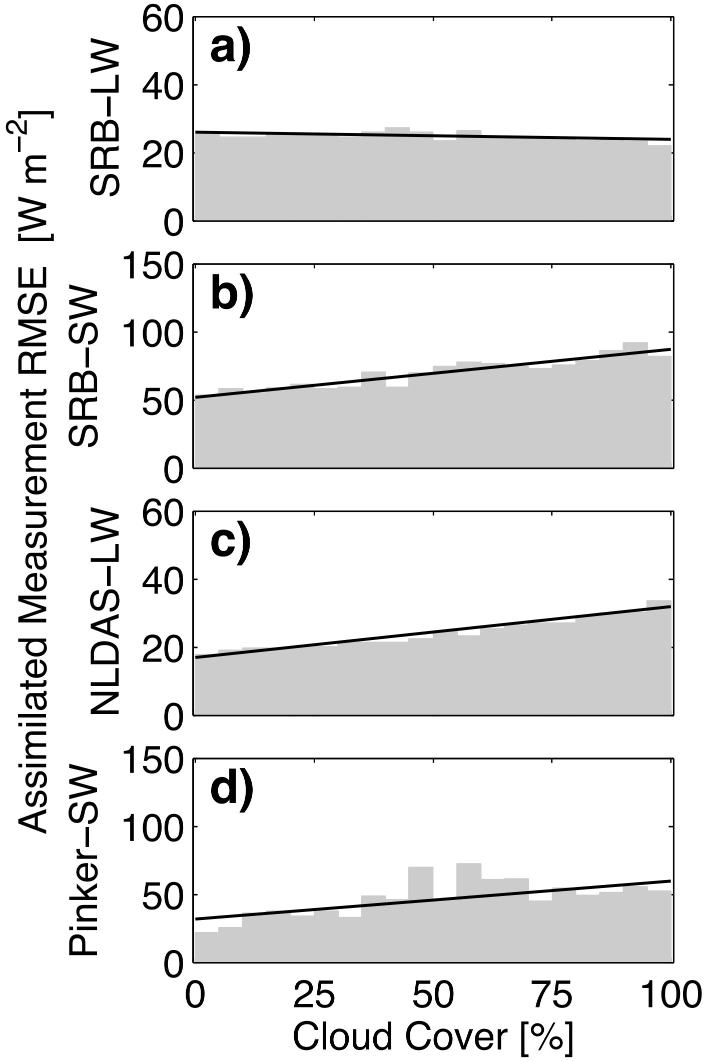
Measurement (plus error): $Z + v_j$

Measurement Model: $\mathcal{M}\left(\mathbf{y}_j^-(\mathbf{x},t),t\right)$

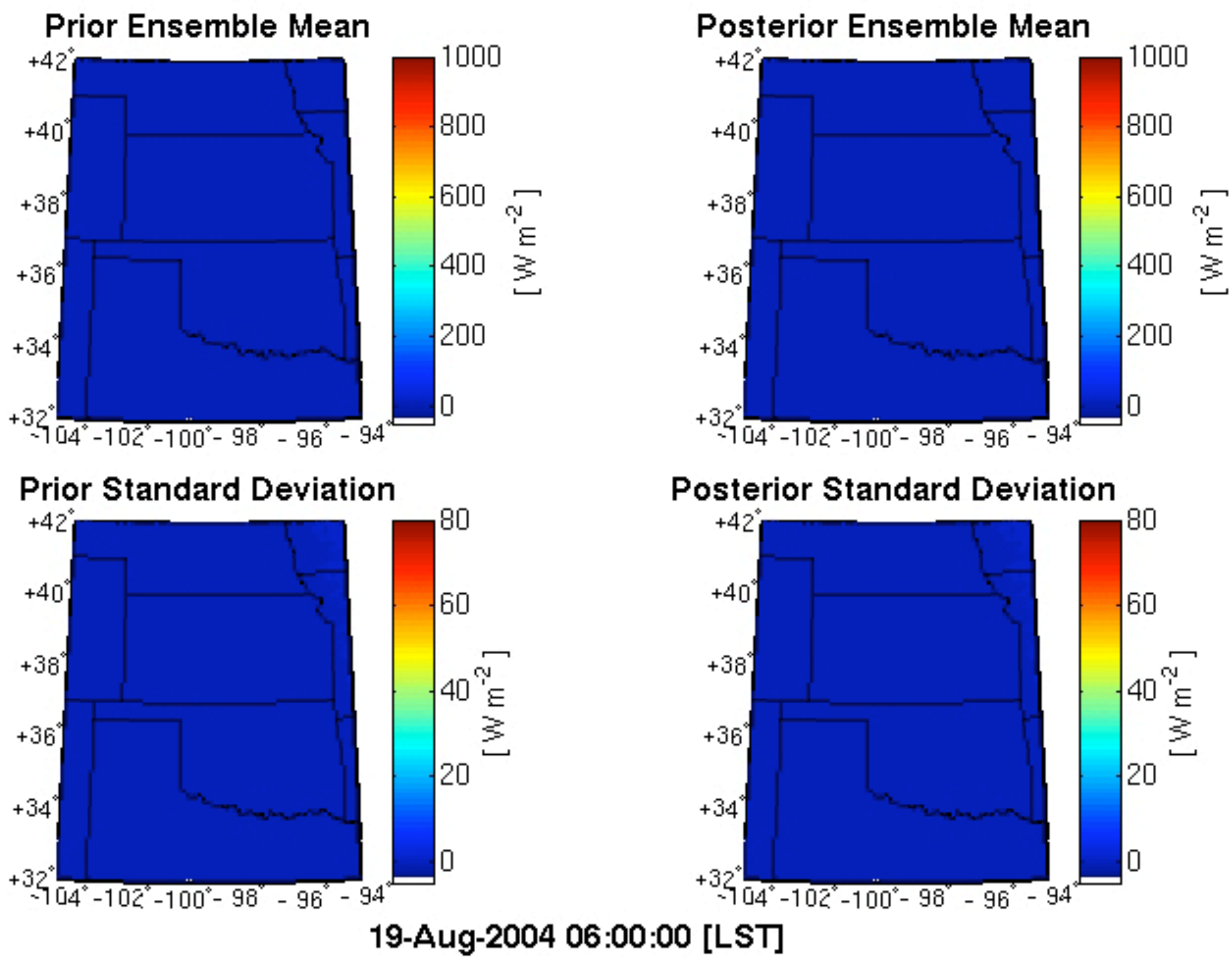
Products for Assimilation



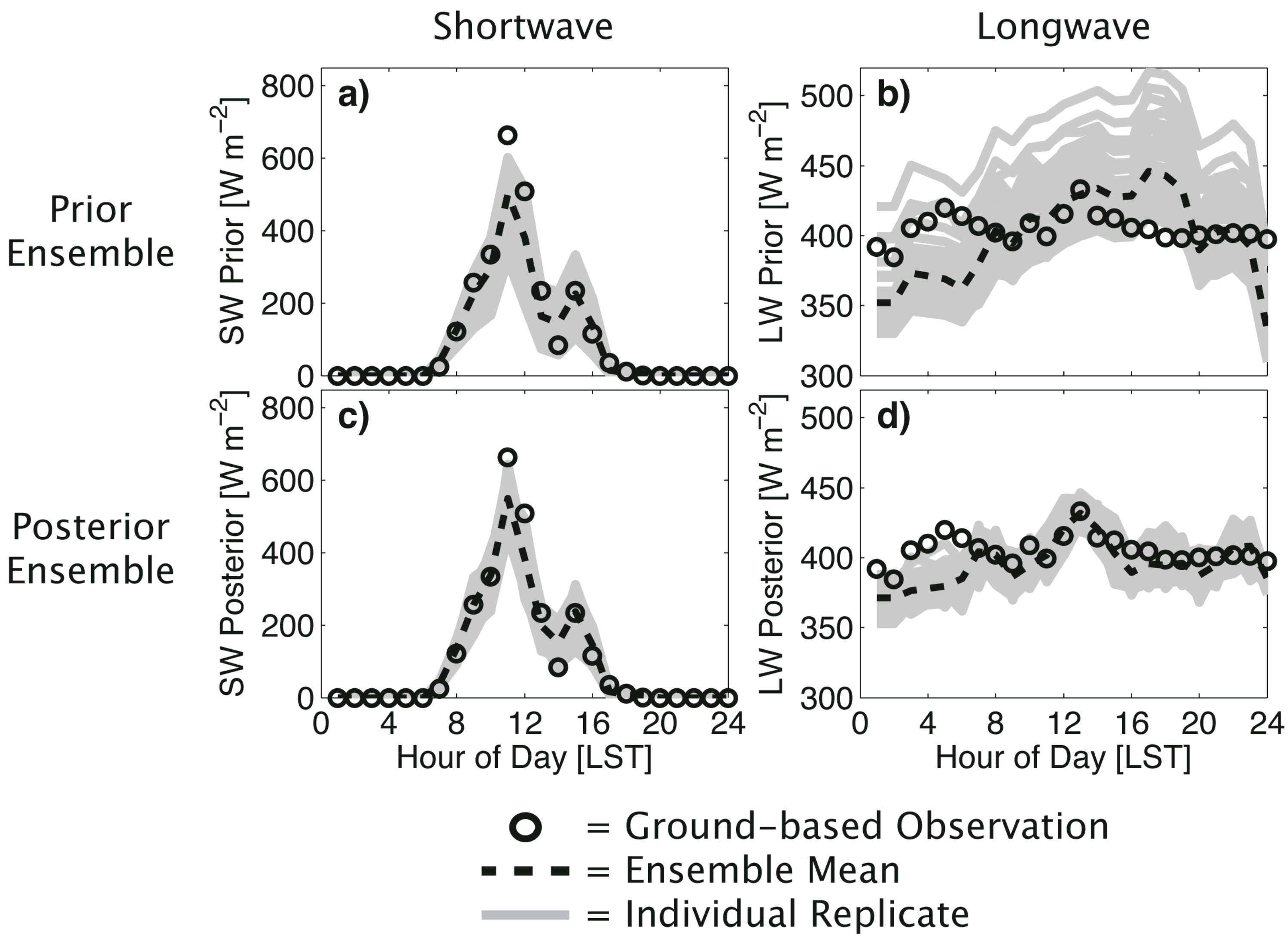
Measurement Error Models



Conditioned Shortwave Example



Prior vs. Posterior Uncertainty



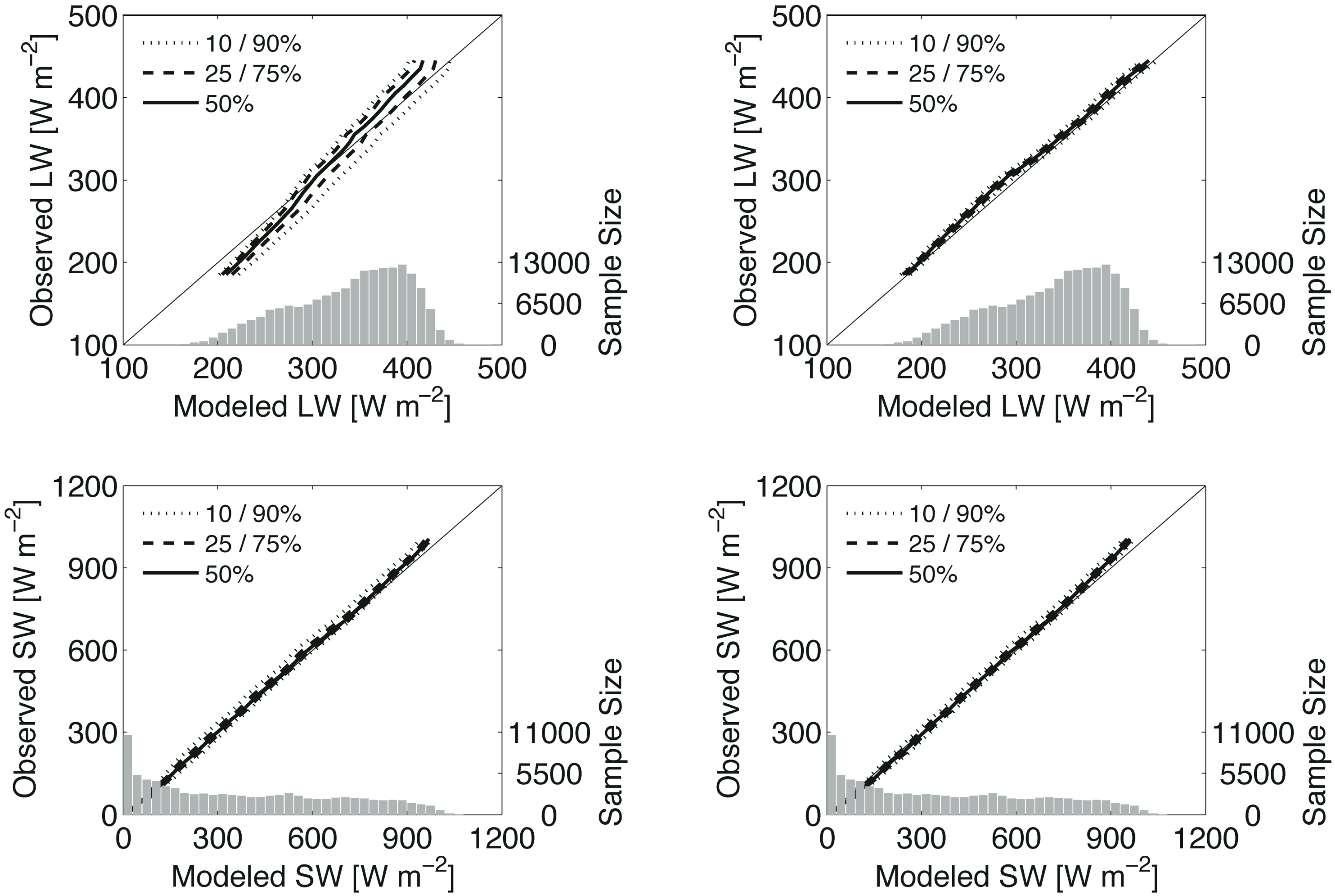
Forman and Margulis [Part 2, In Press]

Ensemble Comparisons

Prior Ensemble | **Posterior Ensemble**

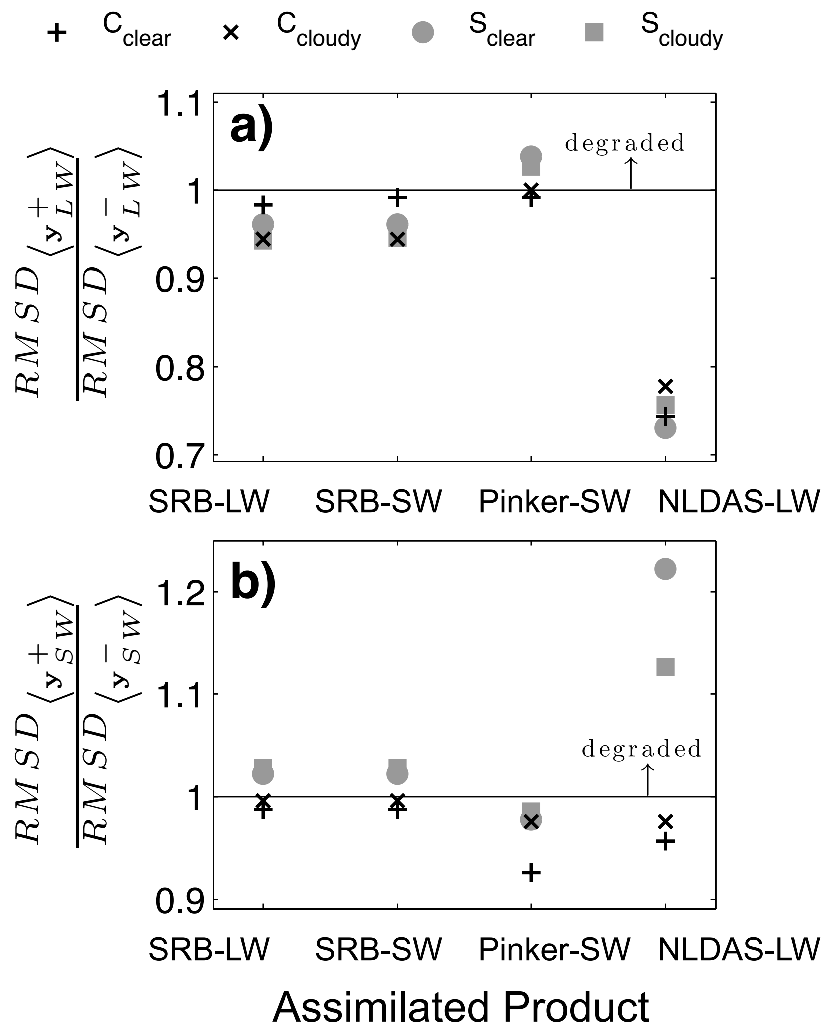
LW Flux

SW Flux



Forman and Margulis [Part 2, In Press]

Prior Uncertainty Matters



Forman and Margulis [Part 2, In Press]

Summary of Findings

- **Ensemble** formulation implicitly contains the **uncertainty**
- Data assimilation framework **adds utility**
  - **Increased accuracy** relative to SIRS
  - **Reduced uncertainty** in posterior ensemble
  - Effectively **downscales measurements**
    - Interpolates in time (smoother only)
    - **Adds value** to existing measurements
  - **Not site specific** and **flexible** with non-Gaussian statistics and non-linear models

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Summary of Recent Research

- **Satellite-based** Assimilation Framework
  - **Global** framework
  - Uncertainty **implicit** within ensemble
    - **Cross**-correlated, **spatially**-correlated
    - Capture complex **spatiotemporal** structure
  - **Improved** accuracy and **reduced** uncertainty
- Captures **key modes** (1^{st} and 2^{nd} moments)
- **Applications** include:
  - Hydrology and earth system science (rad. & ppt.)
  - Water resources management (ppt.)
  - Agriculture (broadband longwave rad.)
  - Renewable energy (broadband shortwave rad.)

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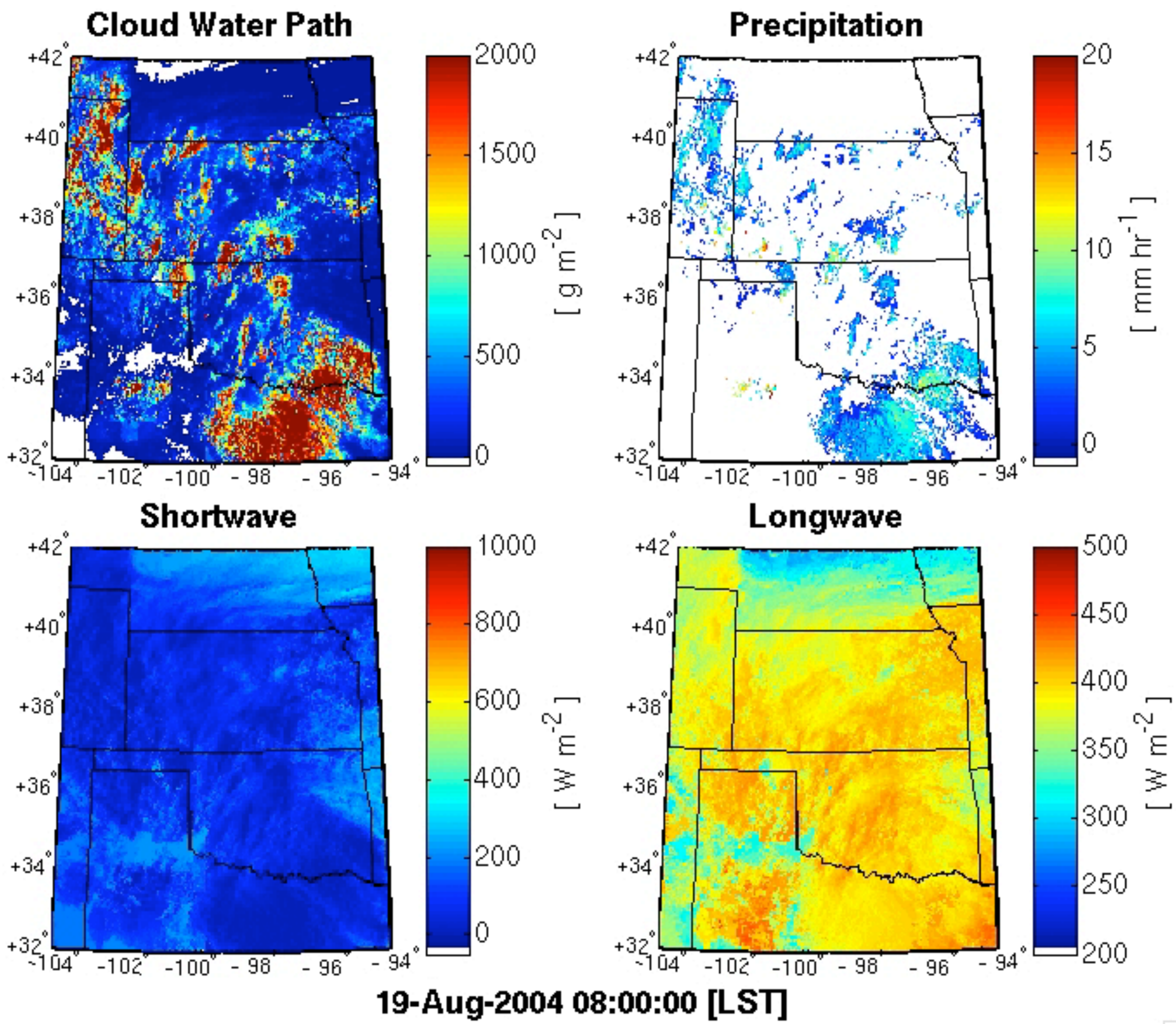
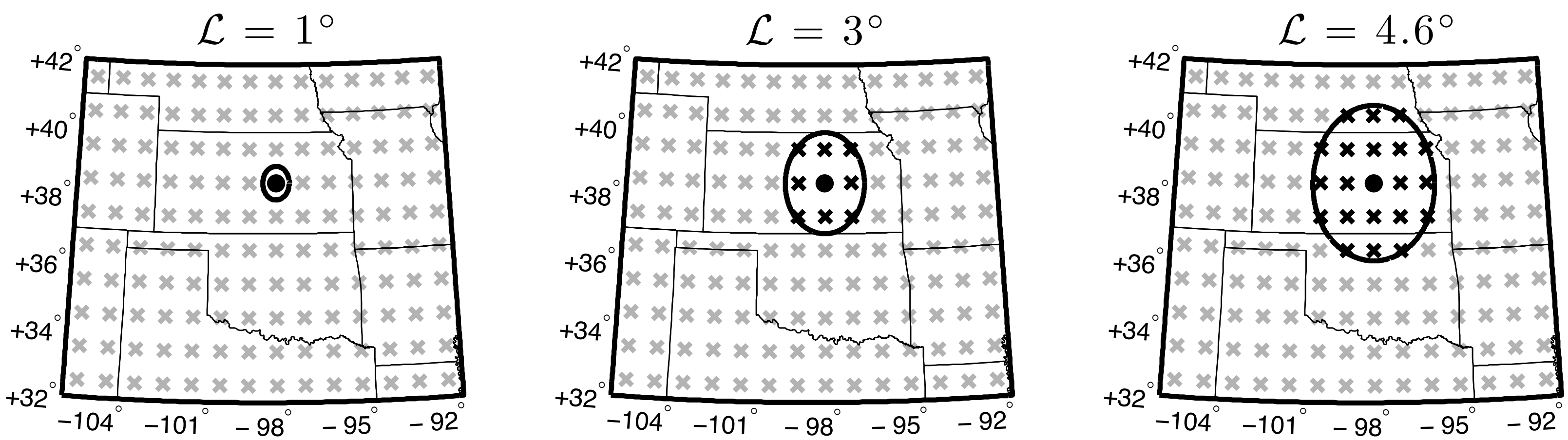
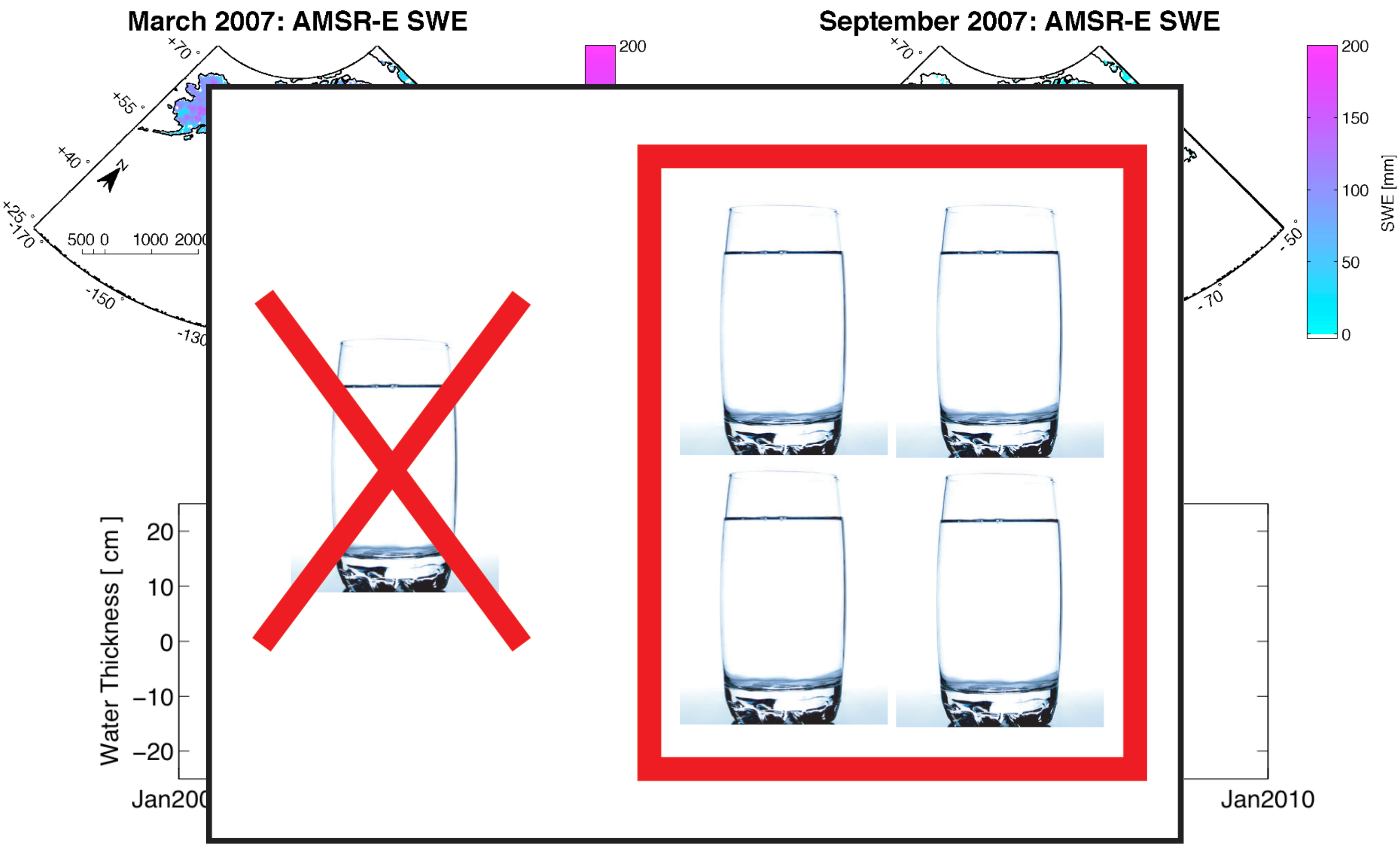
Ensemble Radiation and Precipitation



Horizontal Correlations in "2D" Filter



GRACE DA and SWE Estimation



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